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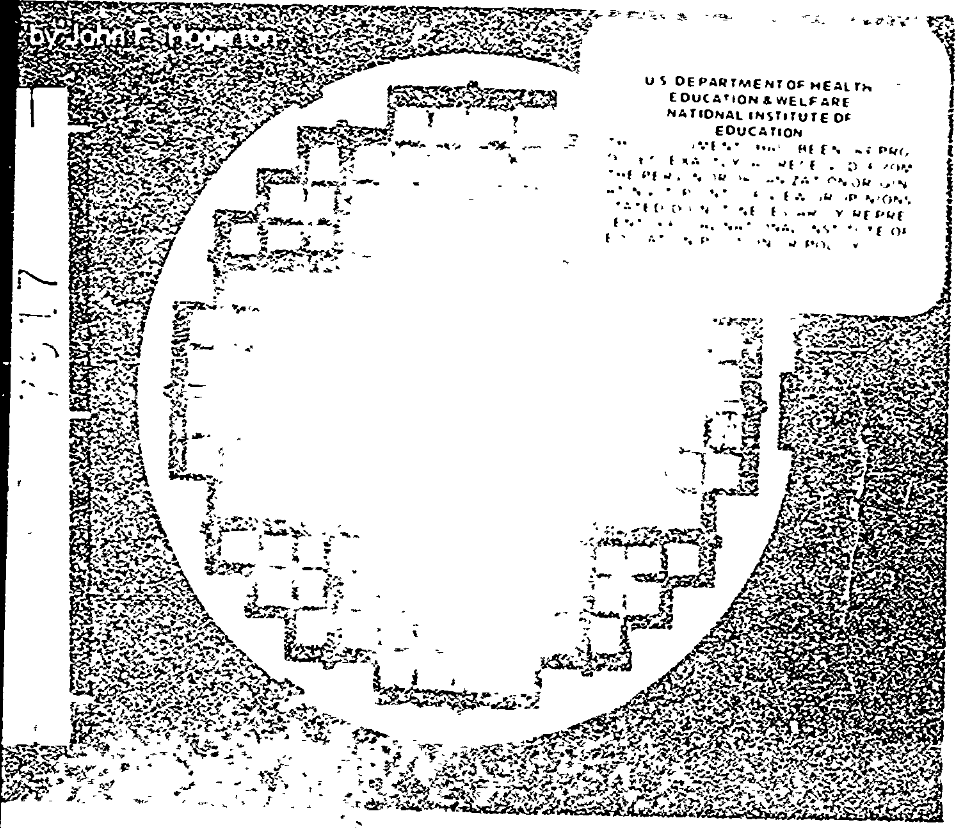
ABSTRACT

This publication is part of the "Understanding the Atom" series. Complete sets of the series are available free to teachers, schools, and public librarians who can make them available for reference or use by groups. Among the topics discussed are: What Atomic Fuel Is; The Odyssey of Uranium; Production of Uranium; Fabrication of Reactor Fuel Elements; Processing of Spent Fuel; The Cost of Atomic Fuel; Atomic Fuel as an Energy Resource; and Atomic Fuel Utilization. A listing of books, reports, articles and motion pictures related to atomic fuels is included. (BT)



by John F. [illegible]

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The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

atomic fuel

by John F. Hogerton

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United States Atomic Energy Commission
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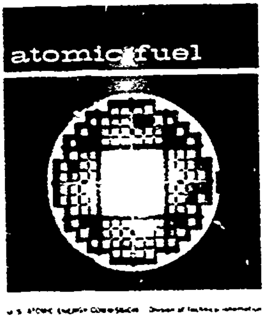


ABOUT THE COVER The cover photograph shows the characteristic geometric arrangement of the fuel core of a power reactor, in this case the Experimental Boiling Water Reactor at Argonne National Laboratory. It is a view looking down into the reactor vessel with the vessel head removed. The glow, known as Čerenkov radiation, is given off by the irradiated fuel.

Courtesy Argonne National Laboratory

ABOUT THE AUTHOR John F. Hogerton is a chemical (B.E., Yale, 1941) and nuclear engineer who has worked in the atomic industry from its beginning. He is now an independent consultant.

Mr. Hogerton was coauthor of the final report on the wartime gaseous diffusion project at Oak Ridge. He also served on the Manhattan Project Editorial Advisory Board, which coordinated the writing of the multivolume National Nuclear Energy Series.

The first edition of the Atomic Energy Commission's four-volume *Reactor Handbook* was edited by Mr. Hogerton. For the American Society of Mechanical Engineers, he contributed to *A Glossary of Terms in Nuclear Science and Technology* and wrote the widely used booklet *Uranium, Plutonium and Industry*. For the AEC he wrote the 1958 Geneva Conference commemorative volume, *Atoms for Peace – U.S.A., 1958*; a one-volume encyclopedia, *The Atomic Energy Deskbook*, published in 1963, and *Nuclear Reactors*, a preceding booklet in this series.

Portions of this pamphlet have been adapted from Report Number 3 of Empire State Atomic Development Associates, Inc., with the kind permission of that organization

atomic fuel

By John F. Hogerton

INTRODUCTION

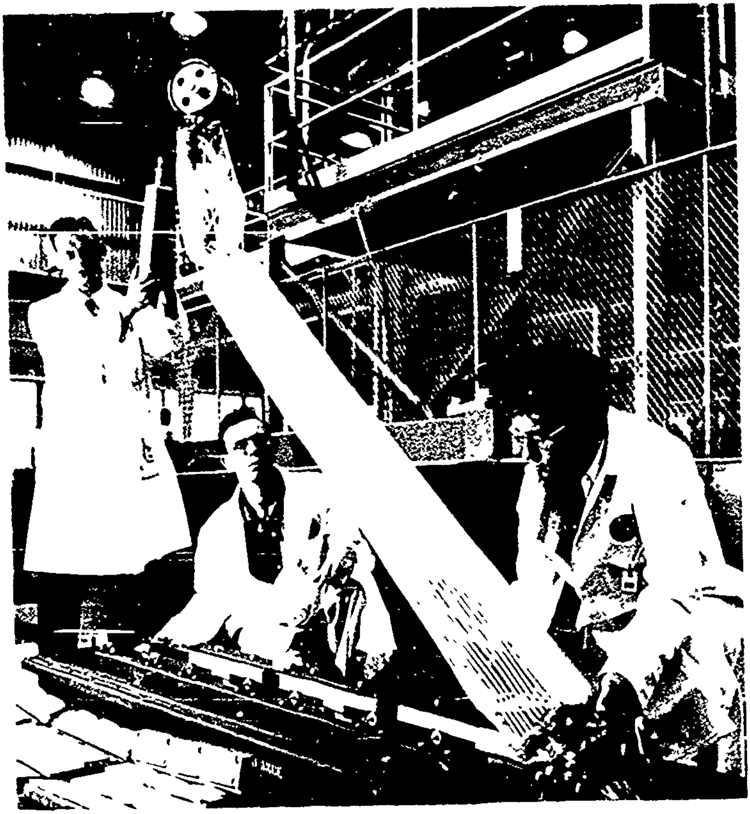
If you lived next to a large coal-fired power plant, you might well wake up several mornings a week to the sound of a freight train rumbling in to deliver fuel. Certainly you would be aware of a big supply operation, for such a plant consumes several thousand tons of coal a day.

But if you lived next to an atomic power plant you probably wouldn't even notice the arrival, every year or so, of a few truck loads of atomic fuel.

The difference in the scale of supply operations reflects the difference in energy content between conventional and atomic fuels. One cubic foot of uranium has the same energy content as 1.7 million tons of coal, 7.2 million barrels of oil, or 32 billion cubic feet of natural gas. In today's atomic power plants only a very small fraction of the potential energy value of the fuel is extracted in a single cycle of operation (see later discussion), but even so a truck load of atomic fuel substitutes for many trainloads of coal.

Let's make the same point in another way. A useful rule of thumb to remember is that for every gram of atomic fuel actually consumed (i.e., made to undergo nuclear fission), approximately one "megawatt-day"* of heat is released.

*A megawatt is 1000 kilowatts. To speak of a megawatt-day of heat means that heat is generated at a rate of 1000 kilowatts over a period of 24 hours.



Fuel element for civilian power reactor. The plastic wrapping keeps the element clean during shipping and handling.

(Courtesy Westinghouse Electric Corp.)

When allowances are made for losses in converting the heat to electric power, this corresponds to an output of about 7000 kilowatt-hours of electricity—enough to take care of the average family's household needs for something like two years. In a modern coal-fired power plant, seven-tenths of a pound of coal is consumed per kilowatt-hour of electrical output. It thus takes 7000 × 0.7 or 4900 pounds (2.5 tons) of coal to do the work that can be done with each gram of atomic fuel consumed.

Still another illustration is the fact that our atomic-powered submarines are capable of cruising several times around the world on a single fuel loading. Even Jules Verne, who had the imagination to write *20,000 Leagues Under the*

*Sea** a century ago, did not foresee so concentrated an energy source.

To return to the atomic power plant in your neighborhood, if you happened to get a glimpse of some of the fuel as it was being unloaded, what would you see? You would see something that might surprise you, namely a number of long and beautifully made metallic objects called "fuel elements." In this booklet we will find out why atomic fuel takes this form, how it is produced, what it costs, and what sort of energy reserve it represents. And in these pages you will find the key to the promise of atomic power.

WHAT ATOMIC FUEL IS

Fissionable and Fertile Materials

By atomic fuel† we mean, in this booklet, fuel for a nuclear reactor, for reactors are the means by which the energy of nuclear fission is harnessed.‡

Atomic fuel consists basically of a mixture of fissionable and fertile materials. The essential ingredient is a fissionable material, a material that readily undergoes nuclear fission when struck by neutrons. The only naturally available fissionable material is uranium-235, an isotope of uranium constituting less than 1% (actually 0.71%) of the element as found in nature.

Almost all the rest (99.28%) of the natural uranium element is the uranium-238 isotope, which is of interest to us for a different but related reason. For when neutrons strike uranium-238 a fissionable material is generally formed, namely plutonium-239. So, although natural uranium actually contains only a little fissionable matter, almost all of it can be converted to fissionable matter.

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* This novel, a forerunner of today's science fiction, deals with the voyage of the *Nautilus*, a futuristic craft powered by electrochemical means. The atomic-powered USS *Nautilus* is its namesake.

† This term may also apply to the heat source in isotope generators, or "nuclear batteries." Here heat comes from radioactive decay. See *Power from Radioisotopes*, a companion booklet in this series.

‡ For information on this subject see *Nuclear Reactors*, a companion booklet in this series.

Because it has the property of being convertible to a fissionable material, uranium-238 is called a fertile material. A second substance that has this property is the element thorium. Its fissionable derivative is still another isotope of uranium, uranium-233.*

Natural and Enriched Fuel

It is possible to achieve a self-sustaining fission reaction with the natural mixture of uranium-235 and uranium-238, so that natural uranium can be used as a reactor fuel. But it is a marginally reactive fuel, and its use imposes certain limitations on reactor design and operation. Enriched fuel is often used to get around these limitations. By enriched fuel is meant fuel having a higher fissionable content than that of natural uranium. Most commonly it is uranium that has been put through an isotope separation process; but it may also be uranium or thorium to which a fissionable substance has been added.

One of the main advantages of enriched fuel is that it gives the reactor designer greater latitude in selecting materials for use in the reactor system (coolant, moderator, etc.). Another advantage is that higher fuel "burnup" can be achieved—i.e., more energy can be extracted before the fuel must be replaced. Still another is that the reactor can be physically smaller.

Many of the reactors built in the United States for civilian power purposes use slightly enriched fuel (3 or 4% fissionable content). In ship propulsion applications where space is at a premium and a very compact power plant is desired, highly enriched fuel (up to about 90% fissionable content) may be used.†

Solid vs. Fluid Fuel

The physical form of the fuel is also important. Some work is being done with fluid fuels—i.e., solutions, slurries, or even molten fuel material—but, except for a few experimental systems, today's power reactors employ solid fuel in metallic or ceramic form.

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* For information on atomic energy in general see *Our Atomic World*, a companion booklet in this series.

† See *Nuclear Power and Merchant Shipping*, a companion booklet in this series.

Fuel Utilization

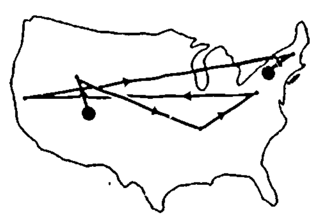
Since uranium-235 is the only naturally available fissionable material, it is the root fuel for atomic power generation. If there were an infinite supply of it, we could afford to neglect the much larger potential reservoir of energy represented by the fertile materials, uranium-238 and thorium. But as it happens, our supply of uranium-235, while large, will not last indefinitely. Therefore, it will be essential in the long run to make the most efficient use possible of all our atomic fuel resources. This will mean operating a network of reactors in such a way that, over a period of time, our resources of fertile materials are efficiently converted to fissionable materials and these in turn are efficiently converted to energy.

We will return to this complex subject in the final section of this booklet. Now let us turn to something simpler, namely the pattern of atomic fuel operations today.

THE ODYSSEY OF URANIUM

When an electric power plant which burns coal, oil, or gas is located far from the source of fuel, an economic penalty in additional fuel transportation costs is incurred. One of the attractions of atomic power to an electric utility company is that, thanks to the compactness of the fuel, locations for atomic power plants can be selected without regard to the distance from the fuel source.

About the only time distance is really important in the life of atomic fuel is when it is in the form of ore. As mined, uranium ore is mostly rock so shipping it very far would be quite costly. But, once the uranium has been separated from the ore dross, it is ready to travel, and travel it does. For example, material mined and milled in Utah may be refined in Missouri, enriched in Kentucky, converted



". . . and travel it does."

in Pennsylvania, fabricated in California, used to generate power in Massachusetts, and reprocessed in New York!

What do these terms mean, and why are all these steps necessary? The best way to answer these questions is to describe the operations involved.* We will do this in three stages: (1) the production of uranium, (2) the fabrication of reactor fuel elements, and (3) the processing of spent fuel. In following the account you may want to refer from time to time to the diagram on page 20. It will be our map.

You may be wondering if radioactivity is much of a problem in the handling of atomic fuel and might like some information on this point before we start our journey. Uranium in its natural state is mildly radioactive, but it does not present a health hazard as long as proper ventilation and clean working conditions are maintained. This statement holds true up until the time uranium is placed in a reactor. During irradiation it becomes contaminated with the intensely radioactive products of the fission reaction and must thereafter be heavily shielded until such time as these contaminants have been safely removed.

PRODUCTION OF URANIUM

Large-scale uranium production facilities have been established in the United States mainly to supply materials for national defense purposes. The amount of uranium presently required for civilian atomic power generation represents but a small fraction of the total production; indeed it is estimated that another decade will pass before the requirements of the power industry match our existing production capability.†

Mining

In the beginning the United States depended primarily on foreign uranium supplies, but we have become the leading

* To simplify our story, we will omit reference to fuels containing plutonium-239 or uranium-233 which are not yet in routine use.

† This statement relates only to uranium production steps (mining, milling, refining, and enrichment) and not to subsequent steps in the chain of atomic fuel supply — namely, the fabrication of fuel elements and the processing of spent fuel (see later discussion).

Uranium mining views. Left, open-pit operation. Above, entrance to underground mine.

Photos Union Carbide Corp.

producer in the free world, accounting in 1962 for about half of the total free-world production.

Practically all the deposits of commercial-grade uranium ore found in the United States to date are in the western part of the country. The major producing areas are northwestern New Mexico, central Wyoming, and the Colorado-Utah border region. The uranium concentration in the ore being mined today ranges from as little as 2 to as much as 20 pounds of U_3O_8* per ton of ore. The average is 5 pounds per ton. Some of the deposits are shallow and mined by open-pit techniques, but the greater part of the ore being produced today comes from underground mines.

*It is the custom to express uranium concentration in raw materials in terms of "black oxide" content. Black oxide is a mixture of uranium oxides formulated as U_3O_8. To obtain the actual uranium content, figures given on this basis should be multiplied by 0.85.

The U. S. Atomic Energy Commission catalyzed the growth of the uranium mining industry by conducting exploration programs* and offering production bonuses and other incentives which stimulated private exploration and mine development activity. When the search for uranium began in earnest in the late forties, there were many lone-wolf prospectors and small mining ventures. It was the "Gold Rush" all over again, except that jeeps and trucks were used instead of burros, and Geiger counters took the place of sieve pans. Today uranium mining is largely done on an industrial scale and is closely integrated with milling operations. And the AEC now buys uranium in concentrated form from uranium mills rather than "in bulk" from miners.

Milling

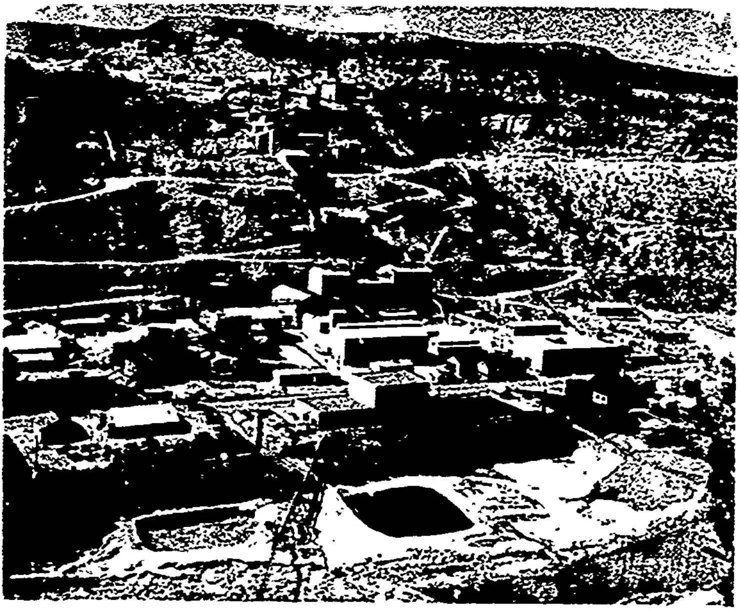
The job of the uranium mill is to get the uranium out of the ore. The ore is first pulverized and is then contacted with a reagent which dissolves the uranium, a step known as leaching. The dissolved uranium is recovered from the "leach liquor" by solvent extraction† or ion exchange‡ techniques and is calcined (roasted) to remove excess water. The product is a crude uranium concentrate, known in the industry as "yellow cake," which usually assays between 70 and 90% U_3O_8.

At this writing more than twenty uranium mills are in operation. They are all privately owned and represent an investment of about $140 million. If run at full capacity, they could produce in excess of 20,000 tons of U_3O_8 per year. Actual production peaked recently at approximately 17,000 tons per year, which was supplied to the AEC under individually negotiated purchase contracts. AEC purchases during the period 1963–1970 are expected to average just under 10,000 tons per year, reflecting a cutback in AEC's annual requirements and a "stretch-out" of procurement commitments.

*In cooperation with the U. S. Geological Survey.

†A chemical separation technique based on preferential solubility in one of two immiscible liquids.

‡A chemical separation technique based on preferential absorption of solute ions on insoluble resins.



Uranium mill at Uravan, Colorado. Courtesy Union Carbide Corp

Refining

For use as reactor fuel, uranium must be refined to purity standards more characteristic of the pharmaceuticals industry than of normal chemical manufacture. The reason is that impurities are "excess baggage" in a nuclear reactor since they absorb neutrons unproductively and thereby detract from the efficiency of the system.

The principal uranium refinery now in operation in the United States is a Government-owned plant located near St. Louis, Missouri. Here the crude concentrates from uranium mills are purified by solvent extraction and then calcined to form essentially pure uranium trioxide (UO_3), a fine powder of brilliant orange hue which has come to be known as "orange oxide." Interestingly, long before the atomic age was born, this same material was produced for use as a coloring agent in chinaware.

Orange oxide from the Missouri refinery is first chemically converted by hydrogenation to uranium dioxide (UO_2), which is then converted to uranium tetrafluoride (UF_4), called "green salt," by reaction with hydrogen fluoride gas.

Uranium metal reduction "bomb", red hot, in furnace immediately after firing. The bomb, charged with a mixture of green salt (UF_4) and magnesium, is heated until the charge ignites spontaneously. The metal then flows to the bottom where it solidifies.

The green salt is shipped to Paducah, Kentucky, site of one of three large uranium enrichment plants (see page 14) where it is reacted with fluorine gas (F_2) to convert it to uranium hexafluoride (UF_6), a volatile compound of uranium used in the enrichment process.

Uranium refining operations are also conducted under an AEC contract at a privately owned plant in southern Illinois. Here mill concentrate is converted directly to uranium hexafluoride and then purified by a distillation process.

Enrichment

We come now to uranium enrichment, which is perhaps the most interesting and certainly the most difficult step in the chain of uranium production. It is also a key step from an economic standpoint, and we will therefore discuss it in some detail.

In uranium enrichment a partial separation of the uranium isotopes is accomplished, resulting in a product called enriched uranium which has a higher-than-normal concentration of uranium-235, and a waste called depleted uranium which has a lower-than-normal concentration of that isotope. Why is this difficult to do? The reason is that the isotopes of an element are chemical twins* and cannot be separated by ordinary chemical methods. The methods used must instead be based on differences in mass or mass-dependent properties. In the case of uranium, the mass difference is proportionately small (235 vs. 238) and hence rather elegant techniques are required.

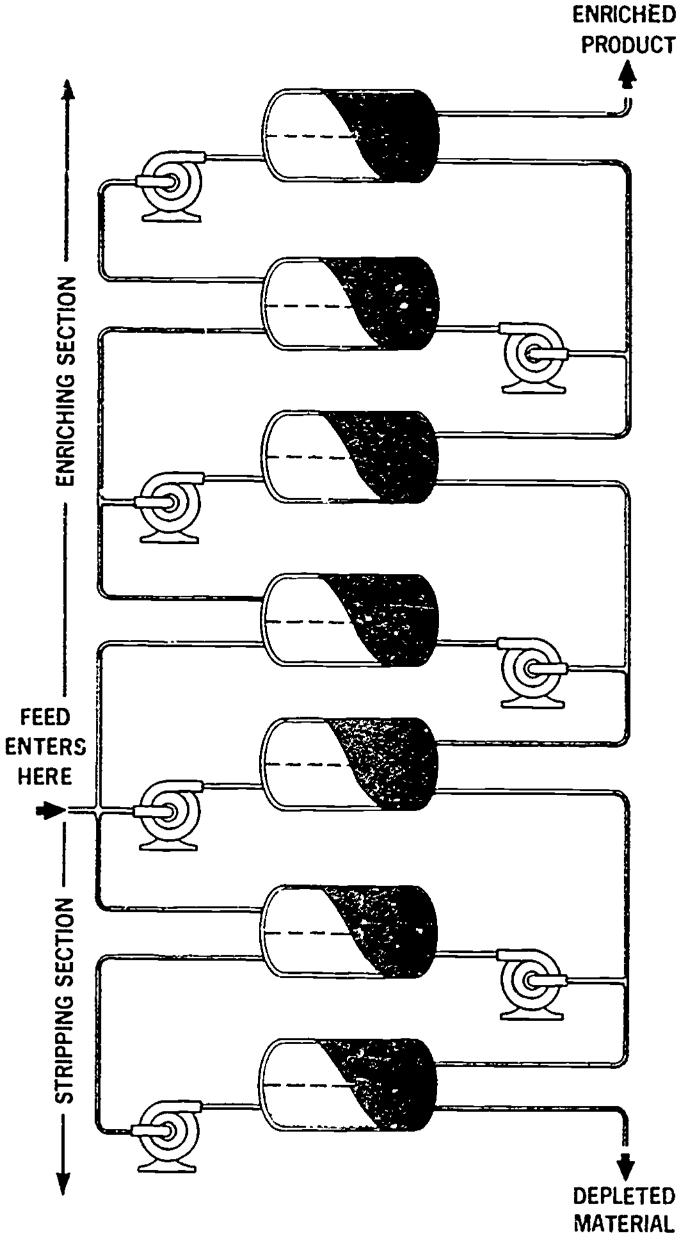
The technique used in the United States is "gaseous diffusion."† As was mentioned before, uranium is processed in the form of uranium hexafluoride, which is a solid at room temperature but sublimes to a gas at a slightly elevated temperature. The gaseous diffusion process could be likened to filtration except for the fact that, instead of depending upon gross differences in the physical size of solid particles, it depends on slight differences in the mobility of gas molecules.

The molecules of a gas are constantly in motion and dart about in random directions. There is an old law of physics which says that, on the average, all molecules of a gas mixture have the same kinetic energy, which is defined mathematically in terms of the mass of the molecule times the square of its velocity ($\frac{1}{2}mv^2$). Thus the lighter molecules of a gas mixture travel at faster speed than the heavier molecules. If advantage is taken of this fact to separate the components of a gas mixture, it follows that the degree of separation which can be accomplished in a single "stage" is a function of the square root of the ratio of the masses of the component molecules. In the case of a mixture of $U^{235}F_6$ and $U^{238}F_6$, the basic "separation factor" works out to be a very small number — 1.0043. This means that many stages are required to accomplish any significant degree of separation of the uranium isotopes.

Typically a gaseous diffusion plant consists of hundreds of stages of equipment connected in series in what is known

* The word "isotope" comes from the Greek "isotopos," meaning "same place," and derives from the fact that the isotopes of an element occupy the same place in the Periodic Table of the Chemical Elements.

† Additional techniques were developed during the wartime Manhattan Project but gaseous diffusion has been found to be the most practical and has been used for all postwar production.



Gaseous diffusion "cascade" for uranium enrichment

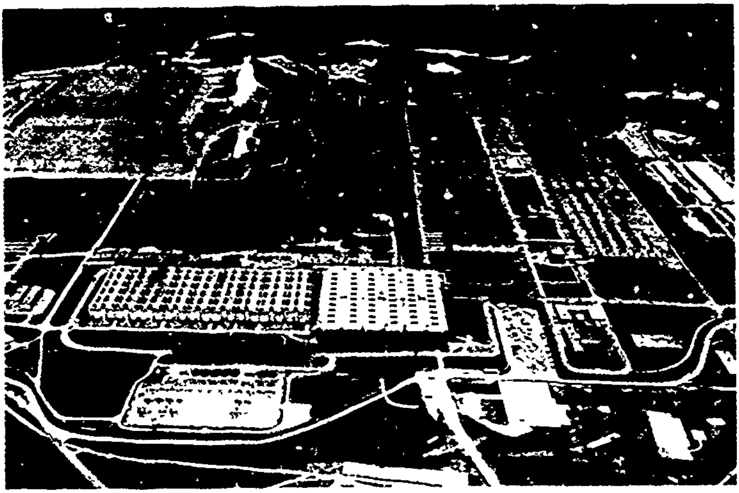
Source: *The Atomic Energy Deskbook*, 1963 as a diffusion "cascade." The principle of operation is illustrated in the diagram on page 12. Let's consider what takes place in a single stage.

The heart of the equipment of a diffusion stage is a chamber divided by a thin and finely porous "barrier" into two zones, one maintained at a lower pressure than the other. The gas mixture enters the higher pressure zone. Conditions are so adjusted that half of it diffuses through the porous barrier into the lower pressure zone and, on leaving the chamber, is directed to the next stage "up" the cascade. The other half flows past the barrier and, on leaving the chamber, is directed to the next stage "down" the cascade. If the two exiting gas streams were analyzed, the one that diffused through the barrier would be found to have been very slightly enriched in the uranium-235 isotope, and, conversely, the one that passed by the barrier would be found to have been very slightly depleted in that isotope. Why? Because the $U^{235}F_6$ molecules, being faster than the $U^{238}F_6$ molecules, tend to strike the barrier more frequently and hence have a better statistical chance of finding their way into the lower pressure zone.

The starting gas mixture is fed to the cascade at an intermediate point. As gas works its way up the cascade it becomes progressively enriched. The product can be withdrawn at any stage above the feed point, depending on the degree of enrichment desired, and is shipped out in pressurized cylinders. Depleted uranium is withdrawn from the base of the cascade and stored.

In addition to the diffusion chambers, the equipment of a diffusion cascade includes pumps to circulate the gas, coolers to remove the heat of pumping, and instruments to control the flow and monitor the operation. The process is carried out at less than atmospheric pressure,* and therefore the entire equipment complex, which if laid out in a

* This has the effect of increasing the "mean free path" of the gas molecules — i.e., the distance they travel between collisions. For efficient separation, this distance should be as large as possible relative to the size of the barrier pores. If it were too small the gas molecules would simply stream through the barrier pores *en masse* and no separation would be achieved.



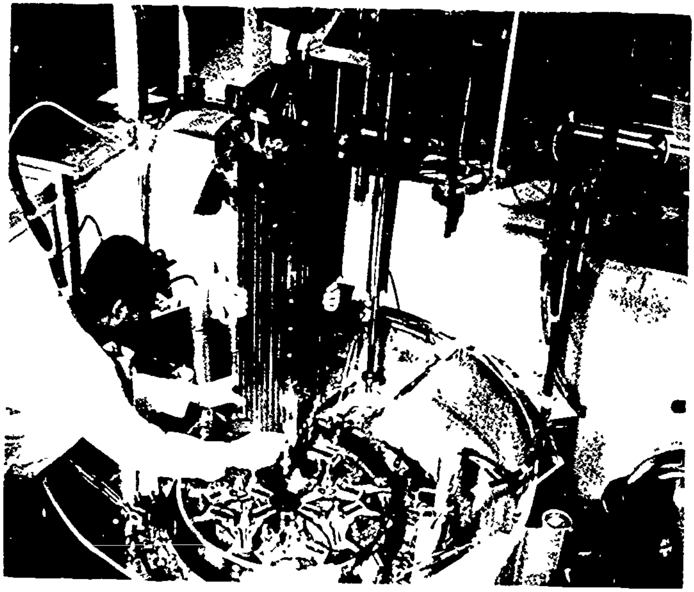
This group of buildings in Oak Ridge, Tennessee, contain the pumps and separation stages which separate uranium-235 from uranium-238 by gaseous diffusion. Some idea of scale may be had by noticing the size of the automobiles in the parking lot in the right foreground. An electric power substation is in the left foreground. The clouds of condensed water vapor in the middle distance are rising from some of the cooling towers.

straight line would stretch several miles, must be essentially vacuumtight.

The three U. S. gaseous diffusion plants are located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. They are Government owned but operated by private contractors. They are of remarkable size, representing a total investment of some $2.4 billion. In 1964 they consumed about 45 billion kilowatt-hours of electricity for driving the gas circulating pumps, etc. This was about 4% of the total amount of electric power generated in the United States.

FABRICATION OF REACTOR FUEL ELEMENTS

As was brought out earlier, the uranium production chain just described now serves defense requirements primarily. From this point forward we will be talking about operations conducted exclusively in support of the civilian atomic



Assembling fuel elements in the core of a reactor

power industry. The dimensions of our discussion will therefore be different, for, instead of dealing with an annual volume of thousands of tons of raw material, we will now be dealing with an annual volume currently measured in hundreds of tons of raw material.

Chemical Conversion

Before reactor fuel elements can be fabricated, the uranium must be chemically converted from the hexafluoride form to the form in which it is to be used in the intended reactor application.

The choice of fuel material for a power reactor depends on several factors. Usually the governing considerations are (1) the ability of the material to withstand the damaging effects of irradiation* and thereby permit high fuel burnup, (2) the chemical and nuclear properties of the material, and (3) ease of fabrication. Uranium dioxide (UO_2) is the material in most common use today, being the standard fuel for

*Swelling, embrittlement, or other physical distortion leading ultimately to mechanical failure reactors of the pressurized and boiling water types. Other ceramic materials, notably uranium carbide, are being developed for use in higher temperature systems such as sodium-graphite and gas-cooled reactors.

The conversion step is a fairly straightforward chemical operation. For example, uranium dioxide is produced by reacting uranium hexafluoride first with water and then with an hydroxide salt. A precipitate results which is calcined to form orange oxide, and this in turn is reduced with hydrogen to form uranium dioxide powder.

Several chemical companies furnish conversion services to the civilian atomic power industry on a routine commercial basis under an AEC license arrangement.

Fabrication

It would be wonderful if atomic fuel could be fed to a reactor much the way coal is fed to a furnace. Something approaching this degree of simplicity may someday be achieved. At present, however, atomic fuel is fabricated into fairly precise shapes, which are fitted together in subassemblies (fuel elements). These in turn are arranged in a carefully designed pattern to make up the "core" of a power reactor.

There are at least two reasons for taking these pains. First, the "geometry" of the fuel is important from a reactor physics standpoint; in other words, a fixed spatial distribution of fuel within the reactor core is required for the system to function properly. Second, because enormous quantities of heat are generated within a very small volume, it is essential to maintain proper channels for coolant flow through the core. The following comparison helps to bring this latter point into clearer focus:

POWER DENSITY*

Modern coal-fired boiler	10
Power reactor of the pressurized water type	2300

*Kilowatts of heat generated per cubic foot of equipment volume.

Another important consideration is the need for "cladding" the fuel, which means enclosing the fuel material in a thin protective sheath. Cladding serves several purposes. It protects the fuel material from corrosion or erosion by the reactor coolant; it locks in the radioactive fission products which are formed as fuel atoms undergo fission; and, in many fuel element designs, it serves a structural function. Cladding introduces certain complications into the design and fabrication of fuel elements. For example, extreme care must be taken to ensure good thermal conductivity (heat transfer) between the fuel material and the cladding; otherwise "hot spots" which could develop in the fuel might cause the cladding to crack or even melt.

Let us now follow the steps in fabricating fuel elements for a pressurized or boiling water reactor. First, small cylindrical pellets are compacted from uranium dioxide powder and inspected for size. Off-specification pellets are either rejected as scrap or are machined to proper size. The pellets are then loaded into thin-walled cladding tubes, made either of stainless steel or an alloy of zirconium. An inert gas (helium) is then introduced into the tubes (for thermal "bonding"), and the tubes are end-capped. A number of tubes are then clustered by means of spacer devices, and the resulting tube bundle is placed in a long rectangular steel or Zircaloy enclosure equipped with end fittings to permit coolant to enter and leave the assembly. This then constitutes a fuel element.

Hundreds of such fuel elements held in position by grid plates in the reactor vessel constitute the reactor core. Careful quality and cleanliness control is exercised throughout the fabrication sequence, and the finished fuel elements are carefully inspected—all in an effort to avoid costly failures during reactor operation.

The fabrication of fuel elements is presently the largest single factor in the cost of atomic fuel (see later discussion). Intensive efforts are being made to reduce the expense of fabrication. For example, in the case of the oxide fuel elements just described, techniques are being developed to permit loading the fuel powder directly into the cladding tubes and compacting it in place, which would eliminate the pelletizing step. Significant gains have been

Steps in the fabrication of pellet-in-tube fuel elements

1. *Equipment for compacting uranium [illegible] powder into pellets. Pellets are sintered in high-temperature furnaces as part of the compacting step.*
3. *After inspection for size the pellets are loaded into cladding tubes.*
4. *Finished tube bundle is checked for dimensional tolerances.*

made in recent years by achieving higher fuel burnups (i.e., longer exposure in the reactor), thereby spreading the cost of fabrication over a larger amount of power output. Significant gains can be expected in future years as the growth of the atomic power market permits fuel fabrication to be carried on a mass production basis.

Fuel elements used in the civilian atomic power industry are fabricated at present by the larger reactor manufacturers, who customarily supply at least the initial core loading for the systems they design. Several additional companies have been licensed to fabricate fuel elements for other reactor markets and represent potential fuel element suppliers for the civilian power market.

PROCESSING OF SPENT FUEL

Why Reprocessing Is Needed

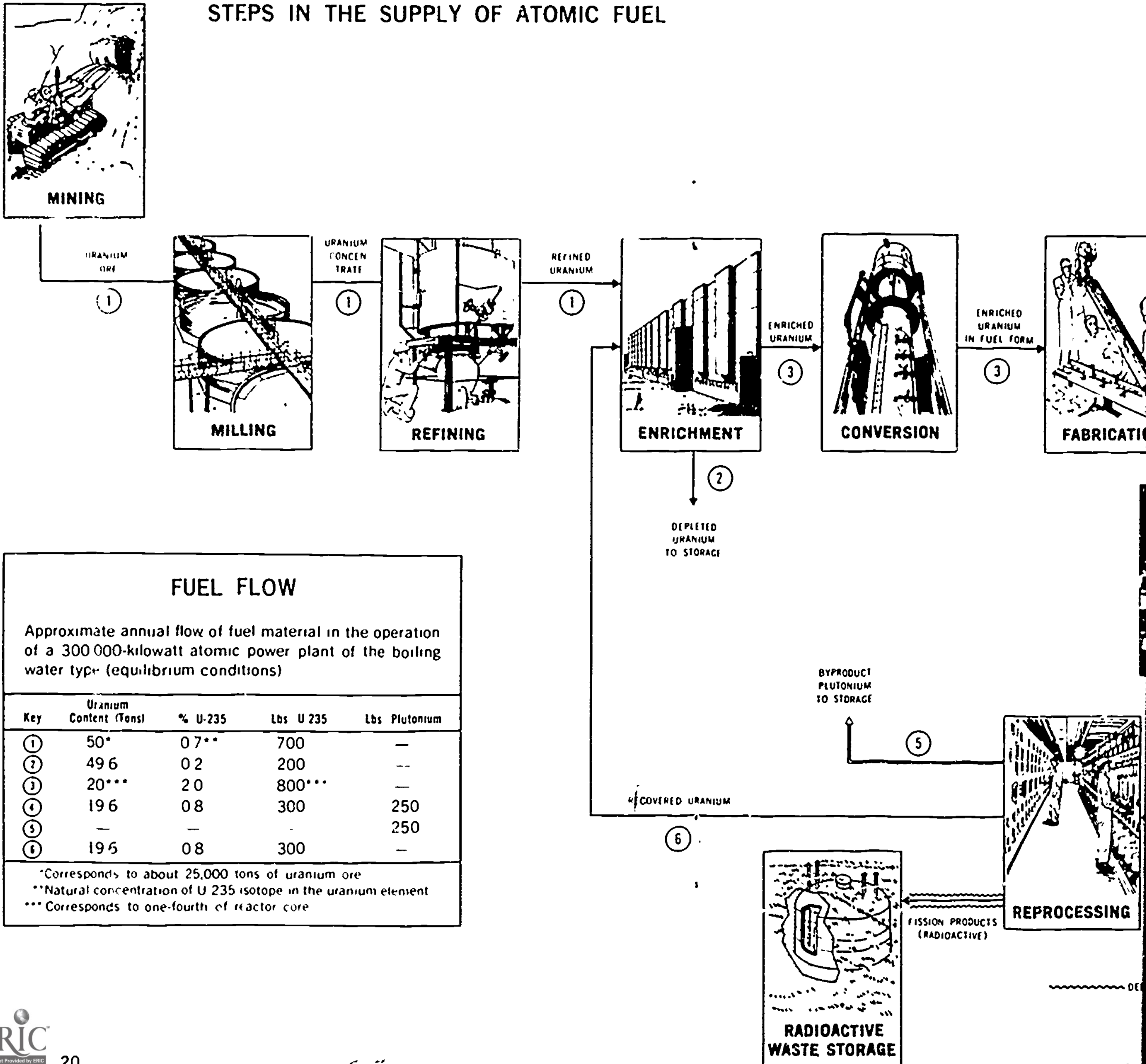
Two factors determine the amount of fuel burnup that can be achieved in a power reactor. The first, mentioned earlier, is radiation damage to the fuel material, one cause of which is the bombardment the material receives from fission fragments. The result is physical distortion of the fuel, leading in time to failure of the cladding and radioactive contamination of the reactor coolant. The second factor is that fission products lower the "reactivity" of the fuel by soaking up neutrons. An excessive accumulation of these "nuclear ashes" would make it impossible to keep the reactor running.*

Because of these effects — and either may be the limiting factor — the fuel must be replaced when only partially consumed. In fact, in most of the reactors being used today for civilian power generation, the fuel must be replaced when only 1 or 2% of the fuel atoms have been used up.

Even with this limited amount of fuel burnup, the cores in question have a useful life of three or four years. In some cases only a third or a fourth of the core is replaced at a time so that refueling is customarily done at approximately yearly intervals.

*Consumption of fuel, of course, also acts to lower the reactivity of the system

STEPS IN THE SUPPLY OF ATOMIC FUEL



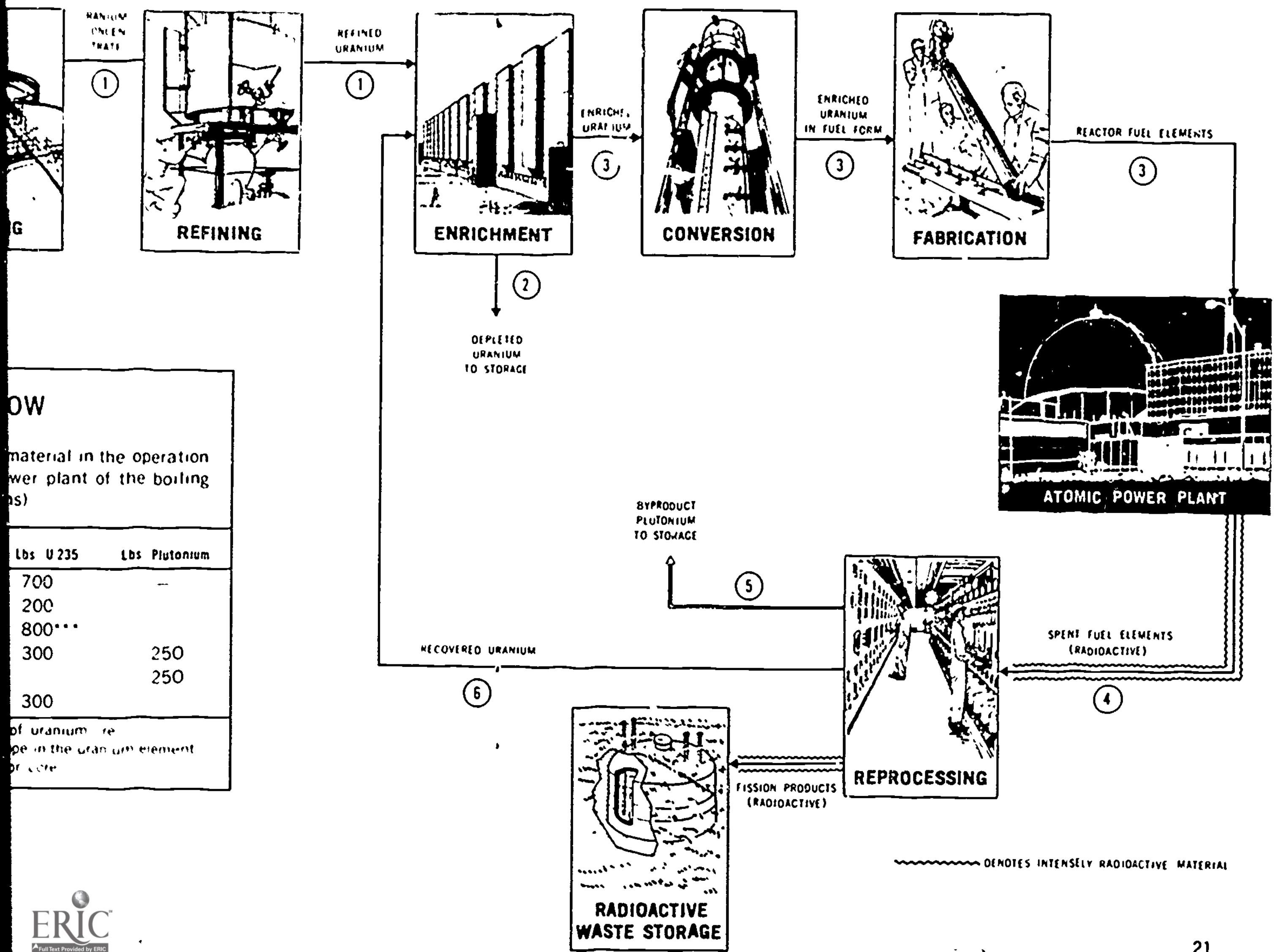
FUEL FLOW

Approximate annual flow of fuel material in the operation of a 300 000-kilowatt atomic power plant of the boiling water type (equilibrium conditions)

Key	Uranium Content (Tons)	% U-235	Lbs U 235	Lbs Plutonium
1	50*	0 7**	700	—
2	49 6	0 2	200	—
3	20***	2 0	800***	—
4	19 6	0 8	300	250
5	—	—	-	250
6	19 6	0 8	300	—

*Corresponds to about 25,000 tons of uranium ore
**Natural concentration of U 235 isotope in the uranium element
*** Corresponds to one-fourth of reactor core

S IN THE SUPPLY OF ATOMIC FUEL



OW

material in the operation
wer plant of the boiling
ns)

Lbs U 235	Lbs Plutonium
700	—
200	
800***	
300	250
	250
300	

of uranium re
pe in the uran um element
or core

As mentioned earlier, another thing that happens as fuel is irradiated is that some fertile uranium-238 atoms are converted to fissionable plutonium-239 atoms. Part of this plutonium undergoes fission in place, thereby contributing to the heat output of the reactor. The rest of it remains intact and thus represents a potential reactor byproduct.

And so there are two excellent reasons for not relegating spent fuel to the scrap heap. One is the obvious desirability of reclaiming the unused uranium, and the other is the plutonium content.

How Reprocessing Is Done

When removed from a power reactor, spent fuel elements are intensely radioactive due to their fission product content. To allow time for some of the radioactivity to die down, they are stored under water for several months, a step known as "decay cooling." Then they are loaded into heavily shielded transfer casks and shipped to a fuel reprocessing plant.

The processing of spent fuel involves a series of operations, most of which are conducted by remote control in equipment installed behind massive concrete shielding walls.

Operating corridor of fuel reprocessing facility at the National Reactor Testing Station in Idaho.

In one method a mechanical tool is first used to cut away as much of the fuel structure supports as possible. The fuel material and residual cladding are then dissolved in acid, and the resulting solution is put through a series of chemical separations accomplished by a solvent extraction process. In the first extraction cycle, most of the fission products are removed. In the second cycle the uranium is separated from the plutonium. In subsequent cycles residual fission products are removed from the uranium and plutonium.

The decontaminated uranium and plutonium leave the plant as concentrated solutions which are readily convertible to other forms. For example, the uranium solution may be converted to the hexafluoride form and recycled through the enrichment process to restore its uranium-235 concentration to the preirradiation level;* or it may be converted to uranium dioxide and blended with material of higher uranium-235 content.

The foregoing description of reprocessing operations is somewhat hypothetical in that, while similar operations have long been conducted in connection with the production of plutonium for defense purposes, facilities designed to handle fuel elements of the type used in civilian power reactors are not yet in service. The reason is that the volume of civilian fuel reprocessing business is just beginning to develop to the point where it will support a commercial reprocessing plant. The first such plant is now being built at a site near Buffalo, New York, and is scheduled to be in service in 1966. Related radioactive waste storage facilities are being provided by the New York State Atomic Research and Development Authority.

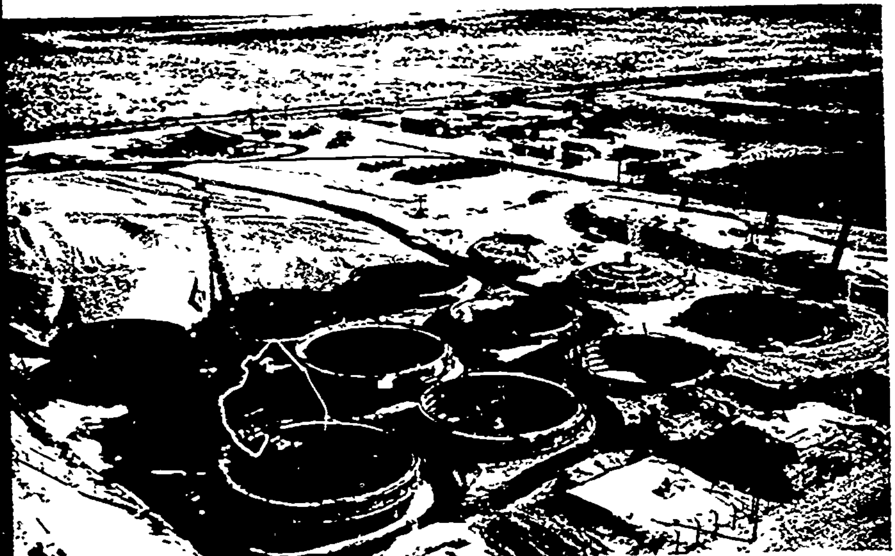
Pending the availability of commercial reprocessing services, the U. S. Atomic Energy Commission has established an interim schedule of reprocessing prices based on cost estimates.

Radioactive Waste Storage

Something like "99.99%" of the radioactive waste matter formed during the operation of an atomic power plant is

*During fuel irradiation uranium 235 is of course consumed. See diagram on page 20.

normally confined within the fuel elements by the fuel cladding and remains confined until spent fuel is dissolved during reprocessing. Most of it then enters the fuel solution and is removed by the extraction sequence described above. The intensely radioactive waste solutions from the extraction process are collected and boiled down to reduce their



Twelve tanks for storage of high level radioactive wastes are shown during construction at the U. S. Atomic Energy Commission's Hanford Atomic Products Operation, Richland, Washington. This "tank farm" is one of several located near the Hanford chemical separations plants from which the wastes come. The tanks are already being "mined" for their valuable store of radioisotopes

volume. Present practice is to store the resulting liquid concentrate in large underground steel tanks. The tanks and their environs are routinely monitored to ensure that no leakage occurs.

This method of radioactive waste storage has been used on a large scale in connection with plutonium production operations for nearly twenty years and has been found to be reliable. It is an acceptable way of handling wastes from civilian power operations in that the expense involved amounts to a very small fraction (2 or 3%) of the total cost of atomic power generation. But it is cumbersome. Some constituents of the wastes take hundreds of years to decay to the point where they can be safely released to the environment; thus there is a problem of "perpetual" tank maintenance.

Several alternative approaches are being studied in an effort to develop maintenance-free methods of storing radioactive wastes. These methods vary according to the degree of radioactivity in the wastes. Naturally, the greatest concern is with the highly radioactive wastes. For these, the techniques receiving the most attention involve calcination and or incorporation in clays and ceramic mixtures so that the waste forms a solid or a glasslike material which can be safely stored in underground vaults without danger of leakage. A further possibility being given preliminary consideration is pumping the wastes into deep underground formations which are geologically cut off from groundwater sources.

To place this subject in proper perspective, it should be added that it will probably be two or three decades before the cumulative volume of radioactive wastes from atomic power generation equals the existing volume of wastes in storage at U. S. plutonium production plants.

It should also be mentioned that progress is being made in developing constructive uses for the longer lived constituents of radioactive wastes. While finding useful things to do with some of the waste matter will not eliminate the storage problem, since even the material used will in time turn up again as waste, continued progress along this line could well affect the pattern of radioactive waste handling.

THE COST OF ATOMIC FUEL

Atomic Fuel vs. Fossil Fuel Costs

You may well have gotten the impression by now that atomic fuel must be a costly commodity to produce. And in a dollars-per-pound sense it is expensive. Following are representative figures for the value of fuel at different stages in the fuel supply chain:

FORM	APPROXIMATE VALUE*
Raw concentrate from uranium mills	$9
Slightly enriched uranium hexafluoride (3% uranium-235) from gaseous diffusion	$115
Fabricated fuel element (pellet-in-tube type)	$165

*Dollars per pound of contained uranium.

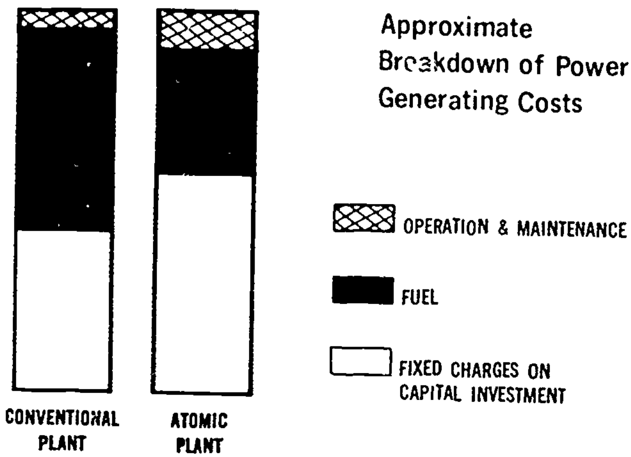
One hundred and sixty-five dollars per pound corresponds to about $11 per troy ounce, which is nine times the current value of silver and nearly one-third that of gold!

But, when you take into account the large amount of energy that is produced from a pound of atomic fuel, the adjective "expensive" no longer applies. In fact, atomic fuel costs less today than coal or oil in important areas of the country; and, as the technology of atomic power advances, it should in time compare favorably with the cheapest fossil fuel available anywhere.

Let's take an example. In New England, where coal and oil have to be shipped in from considerable distances, the fuel portion of the cost of power generation in large modern plants is typically about 3 to $3\frac{1}{2}$ mills per kilowatt-hour.* The projected fuel cost of comparable atomic power plants of 1964 design,† based on firm quotations from reactor sup-

*Ten mills equal one cent.

†Plants that can be ordered today. They would presumably start operation in 1968 or 1969.



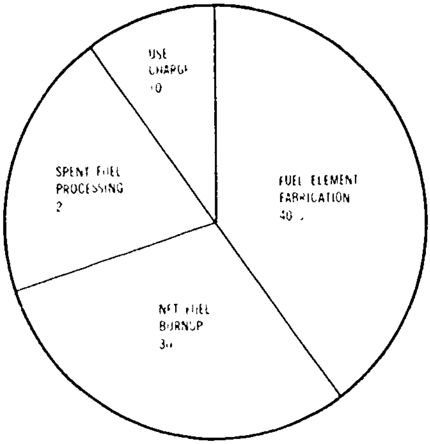
pliers, is in the neighborhood of 2 mills per kilowatt-hour. It should be quickly added that the lower fuel cost is offset by the fact that atomic power plants have higher capital costs and hence must bear higher fixed charges. The net result is that the economics of atomic vs. conventional power generation are presently at about a standoff in New England and other areas presently dependent on relatively high cost fossil fuel.

Approximate Breakdown of Atomic Fuel Costs

Having followed the odyssey of atomic fuel in the preceding pages, you may be interested to know how the costs of atomic fuel break down. The chart on page 28 shows a rough analysis.* Note that the cost of fuel element fabrication is the largest item. Next is the "net fuel burnup" cost, which is in effect the value of the fuel consumed less a credit for byproduct plutonium produced. Next comes the cost of spent fuel processing, which includes the expense of radioactive waste storage. The final item, the "use charge," is in effect a carrying charge on the value of fuel held in inventory.

*Based on fuel for a boiling water reactor of 1963 design.

Breakdown of Atomic Fuel Costs
(Approximate)



In the latter connection, at this writing the basic fuel materials used in atomic power plants are owned by the Government and the use charge is determined by the Atomic Energy Commission. In August 1964 the U. S. Congress enacted new legislation providing for private ownership of these materials. On a private ownership basis, which under the new law becomes mandatory by 1973, the atomic power industry will bear higher inventory carrying charges; thus, this item can be expected to count in the future for more than 10% of the total fuel cost. The new law will bring other changes affecting atomic fuel costs, some of a compensating nature.

ATOMIC FUEL AS AN ENERGY RESOURCE

U. S. Energy Trends

The United States thrives on energy. It takes vast quantities of heat, electricity, and motive power to satisfy our needs. One indication of this is that we use twice as much electricity per capita as is used in England, three and one-half times as much as is used in the Soviet Union, and fifty times as much as is used in Communist China.

The national energy market has been growing at a remarkable rate and no letup is in sight. A report issued in 1962 under Senate auspices by a National Fuels and Energy Study Group predicts that by 1980 our energy needs will be double what they are today. If that proves true, we will use as much energy of all kinds in the next two decades as we have used in our previous history dating back to the American Revolution! And according to many economists the demand may well double again by the end of this century before settling into a more gradual growth pattern.

Only a small fraction (about 4%) of the energy used in the United States comes from water power; the rest comes from the burning of fuel. (See figure on page 30.) Up until now the three fossil fuels—coal, oil, and natural gas—have been carrying virtually all the load. But with atomic power now becoming an economic reality, atomic fuels are beginning to be a factor in the energy marketplace. This development has both short-range and long-range significance as we will now see.

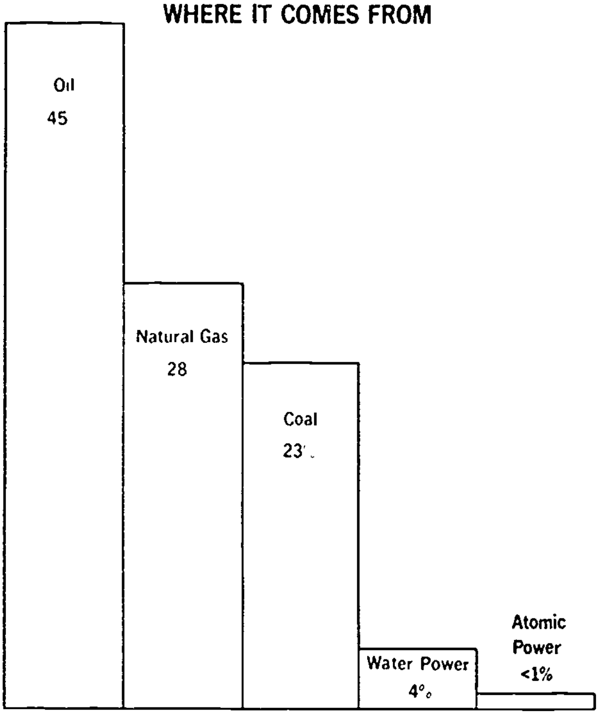
Fossil Fuel Reserves

When estimates of U. S. reserves of fossil fuel are examined in the light of the present pattern and projected growth of the national energy demand, two points stand out. First, our present pattern of fossil fuel consumption is decidedly out of balance (see chart on page 31) with our resources. Coal, which is estimated to account for more than three-quarters of our recoverable fossil-fuel reserves, today fills less than one-quarter of the energy demand. Conversely, oil and natural gas, which are estimated to account for less than one-quarter of the recoverable reserves, today fill more than three-quarters of the demand. We are thus depleting our stocks of oil and gas at a much higher rate than our stocks of coal. To be sure, when necessary we can make synthetic oil and gas from coal, but not without increasing energy costs.

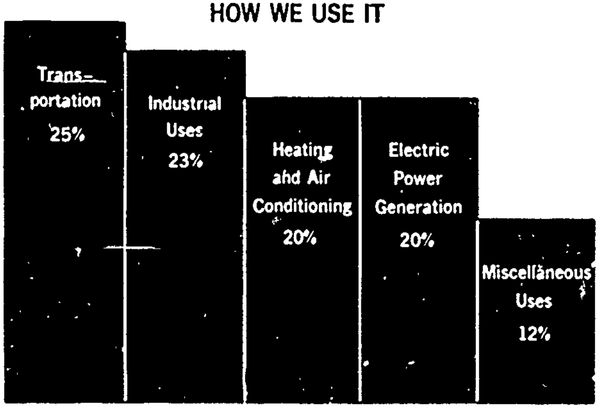
Unfortunately, increased use of atomic energy will not correct this imbalance in our present use of fossil fuel.

Energy Patterns Today*

WHERE IT COMES FROM

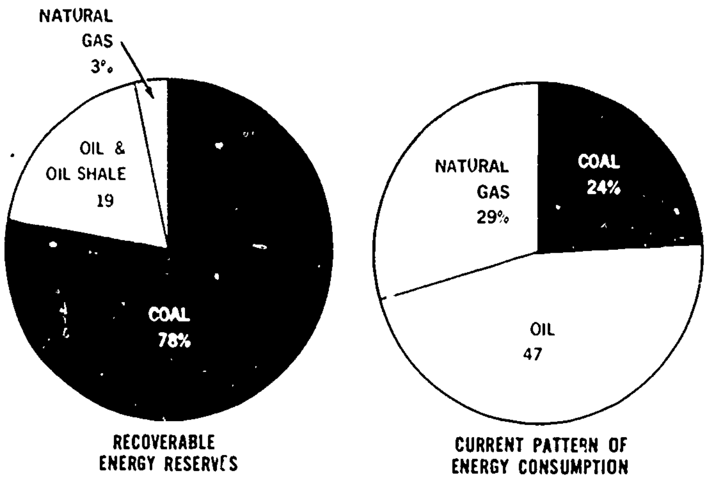


HOW WE USE IT



*Source. U. S. Department of the Interior, 1963.

Imbalance in Our Current Use of Fossil Fuels



Source *Energy Resources Report of the National Academy of Sciences*, 1962

The reason is that atomic fuel is likely to be used chiefly in electric power generation, and in this field coal now supplies more energy than oil and gas combined. However, to the extent that electric utilities elect to use atomic fuel instead of burning oil and gas, atomic energy will help postpone the depletion of these valuable resources.

The second point that stands out is that while we face no early fossil-fuel shortage, our reserves of these fuels are not to be classed as inexhaustible. The report of the National Fuels and Study group estimates that, at today's rate of fuel consumption, our total recoverable reserves of fossil fuel (coal, oil, and gas combined) would last some 800 years. But when projected increases in the rate of consumption are taken into account, the estimate of 800 years shrinks to 200 years or less. And, if low grade sources such as lignite and oil shale are left out of the calculation, the estimate shrinks to 100 years or less. These numbers are by no means to be taken as definitive, since at present we can only roughly infer the extent of our fossil-fuel reserves and since there is also much uncertainty in projecting future energy demand; but they do roughly indicate the situation that might exist if fossil fuel were our only fuel. Let us now see how atomic energy changes the outlook.

Atomic Fuel Reserves

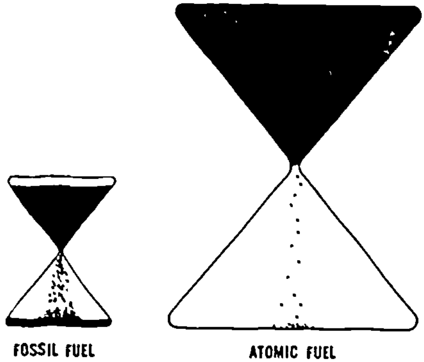
In the next five to ten years, the way atomic fuel will make its contribution to the energy economy of the United States will be in helping to stabilize and, or reduce the cost of electric power generation in areas where the delivered price of fossil fuel is high. In a relatively few locations during this period, atomic power plants may actually produce lower priced power than would have been possible with conventional plants. But for the most part atomic energy will have its effect through the impact its emergence as a competitive means of power generation is certain to have on the price structure of fossil fuel. There are some signs of this already. Also, it will act as a further stimulus for improvements in existing methods of transporting fossil fuel, notably coal.

If we turn to the long-range significance of atomic power, the first question that arises is: how large are our reserves of atomic fuel? The answer is that they are very large indeed. Based on data recently published by the U. S. Atomic Energy Commission,* our reserves of uranium potentially represent ten to fifty times or more the energy equivalent of our reserves of fossil fuel.† And we have additional reserves of atomic fuel in the form of thorium.

In the light of the foregoing, atomic fuel comes into sharp focus as an indispensable long-range energy resource. But, if we are to realize anything like the full potential of this resource, we must learn how to use this fuel much more efficiently than we do at the present time. This brings us to a subject mentioned early in these pages—namely, atomic fuel utilization. It will be our final topic.

*_Civilian Nuclear Power—A Report to the President-1962_, U. S. Atomic Energy Commission.

†Estimate derived from the AEC data using figures given for uranium reserves recoverable from ore at costs up to twelve times present levels. There are almost unlimited reserves of uranium in lower grade deposits.



A Way of Looking at Our Fuels Situation

ATOMIC FUEL UTILIZATION

Converter Reactors

Today's atomic power plants are known as "converters," meaning that they operate with a net loss of fissionable material. You might well ask if this isn't inevitable, and fortunately it is not. For, if you recall our earlier discussion of fissionable and fertile materials, you will remember that fissionable atoms are formed as well as consumed in a nuclear reactor. In reactors of the type most commonly used for civilian power generation today, something like six atoms of new fissionable material are formed for every ten atoms of original fissionable material consumed. This is referred to as a "conversion ratio" of 0.6.

Now it so happens that every time a fuel atom undergoes fission an average of between two and three neutrons is released. Only one of these is needed to keep the fission chain reaction going, so, in principle at least, between one and two neutrons are available to convert fertile atoms present in the fuel into fissionable atoms. In practice, however, some neutrons are inevitably lost by capture in other reactor materials.* In today's power reactors a lot of neutrons are lost in this fashion; hence their generally low yield of new fissionable material.

*Fission products, control material, structural materials, etc.

If we were to continue indefinitely to use converter reactors for power generation, we would run out of fissionable material long before we would run out of fertile material, and once that happened the very large energy potential of the latter would be forever lost.

Another source of inefficiency in our current pattern of atomic fuel utilization is that most of our present reactors produce steam with temperatures and pressures which are too low for efficient conversion of the heat to electricity. This means we are producing less useful power per gram of fuel consumed than we would at higher operating temperatures; or, to put it the other way around, we are consuming more fuel per unit of power output than is necessary.

Breeder Reactors

If neutron losses in a nuclear reactor are kept to a minimum, it is possible to operate with a net gain of fissionable material—i.e., to achieve a conversion ratio in excess of 1.0.* The term for this is "breeding."

Breeding was successfully (albeit marginally) demonstrated as long as eleven years ago in a small reactor experiment, and by 1963 two experimental power reactors designed to perform as breeders are about to be placed in operation. But the development problems still to be solved are extremely difficult, and it is expected that it will be 1980 or thereabouts before large-scale power-breeder reactors begin to be used on any scale in civilian power generation.

There are two basic breeder "fuel cycles":†

FISSIONABLE MATERIAL FED	FERTILE MATERIAL	FISSIONABLE MATERIAL FORMED
1. Plutonium-239	Uranium-238	Plutonium-239
2. Uranium-233	Thorium	Uranium-233

*Technically a conversion ratio in excess of 1.0 is called a "breeding ratio."

†It is also possible to operate breeding "chains" using uranium-235 in combination with a fertile material, but these are not as efficient.

In either case, the maximum breeding gain that can be achieved in a practical system in a single cycle of operation is very small. A term used in this connection is "doubling time," which is the time it takes for a breeder reactor to double its original inventory of fissionable material — i.e., to yield as much net fissionable product as the amount contained in its fuel core plus that tied up in fabrication, reprocessing, etc. Doubling times for power breeders are expected to be of the order of fifteen or twenty years and hence will entail many successive cycles of reactor operation.

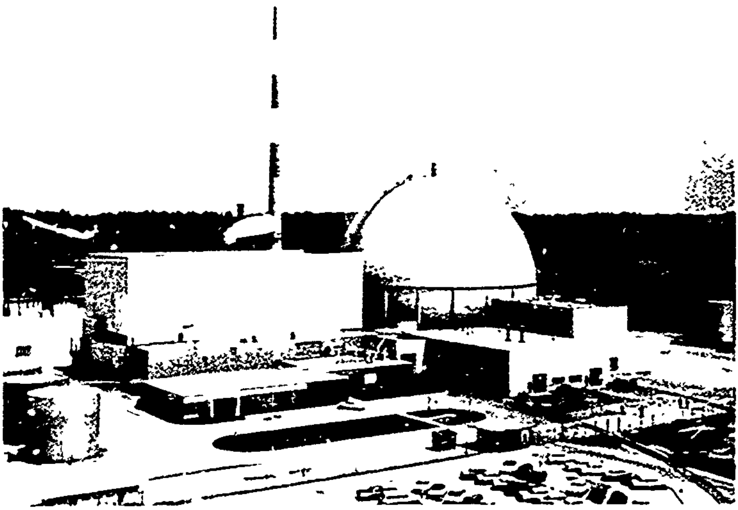
The Logistics of Atomic Fuel Utilization

For some decades U. S. electrical generating capacity has been doubling at approximately ten-year intervals. Atomic power is only beginning to compete in this large growth market and, since the present amount of atomic generating capacity is comparatively small,* its relative rate of growth should be very rapid in the years immediately ahead. (For example, utility companies recently placed orders for four large atomic power plants whose combined capacity exceeded the aggregate capacity of all atomic plants in operation or under construction at the time.)

Clearly then, even if power breeders were available today, they would be unable to generate fissionable material at a fast enough rate to supply the fuel inventories required for new atomic power plants coming on the line. In fact, as long as the *doubling interval* of atomic power generating capacity is shorter than the *doubling time* of power breeders, we will need to operate converter reactors in combination with breeder reactors in an integrated network. In such a network the fissionable material produced by the converters would be used to help fill the inventory needs of new breeders.

Operating converters on a large scale for an indefinite period would place a strain on our atomic fuel resources. It is impossible to predict how long the above-described situation might last, but even the more optimistic studies

*Amounting to less than 1% of the total U. S. electrical generating capacity.



The Dresden Nuclear Power Station, the nation's first full-scale, privately financed atomic power facility, was dedicated on October 12, 1960. The plant, located 50 miles southwest of Chicago, is owned by the Commonwealth Edison Company and was built by the General Electric Company. It uses a boiling water reactor to produce 180,000 electrical kilowatts, which is enough electricity to serve a city of [illegible] persons.

indicate a continued need for converters for at least thirty years. On this basis, and even though in thirty years atomic power is expected to be carrying about half the country's electrical power burden,* our reserves of atomic fuel appear adequate to meet requirements.

Once we reach the stage where in the aggregate we produce more fissionable material than we consume there will be no danger of depleting our fissionable assets; moreover, the economies of fuel utilization would then be such that we could afford to work very low-grade deposits of uranium and thorium. But until that point is reached, careful fuel management will be needed.

*See page 13, *Civilian Nuclear Power — A Report to the President — 1962*, U. S. Atomic Energy Commission.

The Strategy of Power Reactor Development

The considerations mentioned have led to general agreement on the importance of the following parallel lines of power reactor development:

1. Development of improved converters (a) to achieve higher conversion ratios, and (b) to achieve higher power conversion efficiency.
2. Development of breeders.

Both lines of development are being actively pursued by the U. S. Atomic Energy Commission and the atomic power industry.

IN CONCLUSION

We have attempted in this booklet to bring out some of the problems involved in achieving efficient use of atomic fuel as well as to show the promise of this remarkable new source of useful energy. It is hoped that you will want to read further into this interesting and complex subject. To help you do this a list of some useful references has been appended.

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A-Energy to Solve Fuel Problems, *Chemical & Engineering News*, pp. 25-26 (Jan. 28, 1963). A brief summary of information on U. S. fossil-fuel reserves based on a report prepared for the National Academy of Sciences.

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C., and from other AEC film libraries.

Fabrication of Research Reactor Fuel Elements, 20 minutes, color and sound, 1958. Produced by AEC's Oak Ridge National Laboratory. This technical film describes the alloy and powder metallurgy methods of fabricating research reactor fuel elements.

Production of Uranium Feed Materials, 28 minutes, color and sound, 1959. Produced by Continental Productions Corporation for the Oak Ridge Operations Office of the AEC. This semitechnical film describes the step-by-step processing of uranium—from ore concentrates to metal reduction and fabrication—in the feed materials plants of the AEC at Fernald, Ohio, and Weldon Spring, Missouri.

Reactor Fuel Processing, 20 minutes, color and sound, 1958. Produced by AEC's Oak Ridge National Laboratory. This film, describing radiochemical processing of irradiated reactor fuels, covers steps in chemical-separation and waste-disposal operations at pilot-plant facilities.

EBR-II Fuel Cycle Development, 9 minutes, color and sound, 1958. Produced by AEC's Argonne National Laboratory. This film presents some major aspects of the development, in progress, of a completely integrated fuel cycle for Experimental Breeder Reactor-II and includes the remote handling, reprocessing, refabrication, and reassembly of an EBR-II fuel element.

Fuel Fabrication Facility, 9 minutes, color and sound, 1959. Produced by AEC's Argonne National Laboratory. This technical film describes Argonne National Laboratory's fabrication process developments laboratory for the manufacture of unique fuel elements and test pieces containing plutonium.

Plutonium Fuel Fabrication for MTR, 11 minutes, color and sound, 1958. Produced by the Hanford Atomic Products Operation, General Electric Company, as contractor for the AEC at the Hanford Works, Richland, Washington. This technical film details the fabrication of the plutonium which is used as the entire fissionable fuel charge for the Materials Testing Reactor (MTR) at AEC's National Reactor Testing Station in Idaho.

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